Silicon Photonics: A Solution for Ultra High Speed Data Transfer

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***Abstract*— Silicon photonics is the integration of integrated optics and photonics IC technologies in silicon. Silicon photonics has recently attracted a great deal of attention since it offers an opportunity for low cost solutions for various applications ranging from telecommunications to chip-chip inter connects. Two keys to this advancement are the increased speed of communications (now at the speed of light) and the increased amount of data that can be transmitted at once (i.e., bandwidth). Silicon photonics is the study and application of photonic systems which use silicon as an optical medium. The silicon is usually patterned with sub-micrometer precision, into microphotonic components. These operate in the infrared, most commonly at the 1.55 micrometer wavelength used by most fiber optic telecommunication systems. The silicon typically lies on top of a layer of silica in what (by analogy with a similar construction in microelectronics) is known as silicon on insulator (SOI). Today the problems associated with multi-core processors with copper interconnect are Latency, Bandwidth, Power dissipation, Electromagnetic interference and Signal integrity. Micro processor designers use the integration of number of transistors that could be squeezed onto each chip to boost computational horsepower. That in turn caused the amount of waste heat that had to be dissipated from each square millimeter of silicon to go up. One problem we are facing in this effort is that micro processors with large numbers of cores are not yet being manufactured. Fiber optics has a reputation as an expensive solution because of high cost of hardware and Fabrication is done using exotic materials which are costly. The methods used in assembly and package of these components are also expensive. A recent break through in silicon photonics is in the development of a laser modulator that encodes optical data at 40 billion bits per second. Finally reached the goal of data transmission at 40 Gbps speed, matching the fastest devices deployed today with least cost of processing and showing the ultimate solutions to the problems associated with copper interconnects in multi-core processors and expensive fiber optics.**

***Index Terms* — silicon photonics, Light source, silicon waveguide, silicon modulator, Photo detector, indirect band gap, compatibility-quad, gallium nitride**

I. Introduction

Silicon is the principal material used in semiconductor manufacturing today because it is plentiful, inexpensive, well understood by the semiconductor industry. Silicon photonics is a term given to the science of optical communications, a science that is now looking to do what has been done with so many other electronic devices; make them smaller, faster, and cheaper; specifically, to bypass current barriers in optical communications by integrating optical computing with semiconductor chips. Silicon photonics aims to provide inexpensive silicon building blocks that can be integrated to produce optical products that solve real communication problems for consumers. Silicon is an especially useful material for photonics components because it is transparent at the infrared Wavelengths at which optical communication systems operate.

Silicon photonic devices can be made using existing semiconductor fabrication techniques, and because silicon was already used as the substrate for most integrated circuits, it was possible to create hybrid devices in which the optical and electronic components were integrated onto a single microchip.

II. Componets of optical communication

At present optical communication networks consist of three key building blocks: optical fiber, light sources, and light detectors.

Optical fibers are now ubiquitous. They are the long, thin glass or Teflon fibers used to propagate a light signal down their length. This signal can be manipulated at both ends so as to code and decode the 1s and 0s that comprise the digital data domain. While initial use of optical fiber involved a single stream of data, this was soon improved upon with Multimode Fibers (MMFs). These fibers can support several light sources by using slightly different angles when propagating light down the length of the fiber, thus dramatically increasing a single fiber's bandwidth. With such improvements in the ability to manipulate the digital signal (called modulation), data speeds are now at 10 Gb/s and could theoretically reach 20 Tb/s. Extrapolate this out to the bundle of fibers that typically run down most residential avenues today delivering voice, TV, and data and one starts to believe in the theory of 'more than we could ever use'. These fibers have made their way beyond the large deployments of the cable and telecommunications providers and into even small data centers. For instance, it is not at all uncommon to find mass storage systems attached to high end computing systems via an optical fiber link. Fiber is even finding its way into 'the last mile', being offered by some cable providers delivering optic communications all the way to your home.

DOI: 01.IJCOM.02.03. 524

Light sources are needed to generate the signal which travels down the optical fiber. These are typically the most costly element in optical communications. Most widely used are the Laser Diode (LD) and the Light Emitting Diode (LED). These are both semiconductor devices, but as will be later explained, not on the miniaturized scale needed for Silicon Photonics. Key to the use of any light source is ensuring it is aligned with the optical fiber so that light entering the fiber is propagated down its length with minimal loss. Of particular impact is loss related to back-reflection at the point of entry. If the light source is not aligned perfectly, some light will catch the edges of the fiber and reflect back into the source, causing loss in signal strength, as well as creating potential problems for the light source itself in the form of interference and built up of heat.

A second key aspect in the use of a light source is the form of manipulation or modulation. To represent binary data, the light must represent two distinct levels. In optical communications, this is done by turning the light on and off. There are two common ways, called modulation techniques, by which this is done. The most obvious is to turn the light source on and off by applying or removing voltage to the source (called direct modulation). While this seems straight forward, it has problems. The two most impacting being the time required and a distortion in the signal called frequency chirp (Herve, Ovadia 2004). A second method, 'external modulation,' minimizes these problems. Here the light source is run in Continuous-Wave (CW) mode, meaning it is never shut down, while an external (to the light source) component determines when light is allowed to pass into the fiber or not. The final component necessary for optical communication is the light detector that as its name suggests, 'detects light' at the receiving end. More importantly, it discriminates between light and no light to reconstruct the patterns of the modulator on the transmitting end and convert this back into an electrical signal to be used by the receiving device as digital data. These are also typically semiconductor-based devices called photodiodes, but once again these are of a scale too large to integrate onto a microchip with other components.

III. CMOS MANUFATURING PROCESSES

There is an inexorable trend in the electronics industry to make things smaller, faster and cheaper. To fully understand the scope of Silicon Photonics requires understanding the processes involved in creating a CMOS chip. CMOS chips are built on a substrate of Silicon (Si). Silicon is used because of its properties as a natural semiconductor – it can function equally well as a conductor or an insulator of electricity – and it is both inexpensive and abundant (it is made from sand). A wafer of silicon is produced and a layer of Silicon Dioxide (SiO_2) is placed on top of the wafer. This is then followed up with a layer of chemical called a 'photoresist', so named because when exposed to a certain wavelength of light the chemical hardens. Using that wavelength, a pattern is laid out in the layer of photoresist; then the photo resist that was not exposed to light is washed away. The surrounding layer of SiO_2 that is not masked by the hardened photoresist can then be etched from the wafer. The hardened photoresist is then taken off and what is left is the electronic component or circuit. In most cases, this process is performed many times over and layer upon layer is built up to form complex components and circuits. The layers them selves can be composed of different materials and sometimes the base layer of Si itself is used by altering its chemical/electrical properties. But in all cases, the process is basically the same: masking of some sort, alteration of that which is not masked, then finalized what remains. This process has enabled the miniaturization of individual electronic components initially the size of a dime or a quarter along with electronic circuits that would incorporate countless meters of wiring down to something measured in nanometers (nm).

IV. NEED FOR SILICON PHOTONICS

Fiber-optic communication is the process of transporting data at high speeds on a glass fiber using light. However, this technology is an expensive solution. The components are typically fabricated using exotic materials that are expensive to manufacture [7].

The trouble with multi-core processors is another challenge. Programming multi-core processors is a complex process at the same time it is quiet tough to implement. Here the main goal was to develop high-volume, low-cost optical components using standard CMOS processing [4] the same manufacturing process used for microprocessors and semiconductor devices. Moreover, manufacturing silicon components in high volume to the specifications needed by optical communications was comparatively inexpensive. Fiber is already being used to shuttle data from computers to data storage devices and from computer to computer. With a potential of terabits in the optical domain and problems starting in the gigabit range for metal wire circuits, a bottleneck becomes evident.

Silicon Photonics showed promise as the answer. The idea was to build all the components for optical circuits with the CMOS manufacturing processes and eliminate the bottleneck. Extend the optical communication path inside the computer, inside any electronic devices in the path, perhaps even all the way into the microprocessor and memory chips themselves.

Silicon's key drawback was that it cannot emit laser light. However, silicon can be used to manipulate the light emitted by inexpensive lasers so as to provide light that has characteristics similar to more-expensive devices. This was just one way in which silicon can lower the cost of photonics

V. PHYSICAL PROPERTIES

The propagation of light through silicon devices was governed by a range of nonlinear optical phenomena including the Kerr effect, the Raman effect, two photon absorption and interactions between photons and free charge carriers. The presence of nonlinearity was of fundamental importance, as it enabled light to interact with light, thus

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permitting applications such as wavelength conversion and all-optical signal routing, in addition to the passive transmission of light.

A. Optical guiding and dispersion tailoring

Silicon is transparent to infrared light with wavelengths above about 1.1 micrometers .Silicon also has a very high refractive index, of about 3.5.The tight optical confinement provided by this high index allows for microscopic optical waveguides, which may have cross-sectional dimensions of only a few hundred nanometers. This is substantially less than the wavelength of the light itself, and is analogous to a sub wavelength-diameter optical fibre. Single mode propagation can be achieved, thus (like single-mode optical fiber) eliminating the problem of modal dispersion.

The strong dielectric boundary effects that result from this tight confinement substantially alter the optical dispersion relation. By selecting the waveguide geometry, it was possible to tailor the dispersion to have desired properties, which was of crucial importance to applications requiring ultra-short pulses. In particular, the group velocity dispersion (that is, the extent to which group velocity varies with wavelength) can be closely controlled. In bulk silicon at 1.55 micrometers, the group velocity dispersion (GVD) is normal in that pulses with longer wavelengths travel with higher group velocity than those with shorter wavelength. By selecting suitable waveguide geometry, however, it was possible to reverse this, and achieve anomalous GVD, in which pulses with shorter wavelengths travel faster. Anomalous dispersion was significant, as it was a prerequisite for modulation instability.

In order for the silicon photonic components to remain optically independent from the bulk silicon of the wafer on which they were fabricated, it was necessary to have a layer of intervening material. This was usually silica, which has a much lower refractive index (of about 1.44 in the wavelength region of interest), and thus light at the silicon-silica interface had (like light at the silicon-air interface) total internal reflection, and remained in the silicon. This construct is known as silicon on insulator. It was named after the technology of silicon on insulator in electronics, whereby components were built upon a layer of insulator in order to reduce parasitic capacitance and so improve performance.

B. Kerr nonlinearity

Silicon has a focusing Kerr nonlinearity, in that the refractive index increases with optical intensity. This effect was not especially strong in bulk silicon, but it was greatly enhanced by using a silicon waveguide to concentrate light into a very small cross-sectional area. This allowed nonlinear optical effects to be seen at low powers. The nonlinearity could have been enhanced further by using a slot waveguide, in which the high refractive index of the silicon was used to confine light into a central region filled with a strongly nonlinear polymer.

C. Two-photon absorption

Silicon exhibits two-photon absorption (TPA) [9], in which a pair of photons can act to excite an electron-hole pair.[8] This process was related to the Kerr effect, and by analogy with complex refractive index, could have been thought of as the imaginary-part of a complex Kerr nonlinearity. At the 1.55 micrometer telecommunication wavelength, this imaginary part was approximately 10% of the real part.

The influence of TPA was highly disruptive, as it both wasted light, and generated unwanted heat. It could be mitigated, however, either by switching to longer wavelengths (at which the TPA to Kerr ratio drops), or by using slot waveguides (in which the internal nonlinear material has a lower TPA to Kerr ratio). Alternatively, the energy lost through TPA could be partially recovered (as is described below) by extracting it from the generated charge carriers.

D. Free charge carrier interactions

The free charge carriers within silicon can both absorb photons and change its refractive index. This is particularly significant at high intensities and for long durations, due to the carrier concentration being built up by TPA. The influence of free charge carriers was often (but not always) unwanted, and various means had been proposed to remove them. One such scheme was to implant the silicon with helium in order to enhance carrier recombination. A suitable choice of geometry could also be used to reduce the carrier lifetime. Rib waveguides (in which the waveguides consist of thicker regions in a wider layer of silicon) enhanced both the carrier recombination at the silica-silicon interface and the diffusion of carriers from the waveguide core.

A more advanced scheme for carrier removal was to integrate the waveguide into the intrinsic region of a PIN diode, which was reverse biased so that the carriers were attracted away from the waveguide core. A more sophisticated scheme still, was to use the diode as part of a circuit in which voltage and current are out of phase, thus allowing power to be extracted from the waveguide. The source of this power was the light lost to two photon absorption, and so by recovering some of it, the net loss (and the rate at which heat is generated) could have been reduced.

As is mentioned above, free charge carrier effects could also be used constructively, in order to modulate the light.

E. Raman effect

Silicon exhibits the Raman-effect, in which a photon is exchanged for a photon with a slightly different energy, corresponding to an excitation or a relaxation of the material. Silicon’s Raman transition was dominated by a single, very narrow frequency peak, which was problematic for broadband phenomena such as Raman amplification, but was beneficial for narrowband devices such as Raman lasers. Consequently, all-silicon Raman lasers were fabricated.

VI. Essential components

In order to”siliconize” photonics, six main building blocks were used:

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• An inexpensive light source
• Devices that can route, split, and direct light on the silicon chip
• A modulator to encode or modulate data into the optical signal
• A photo detector to convert the optical signal back into electrical bits
• Low-cost, high-volume assembly methods
• Supporting electronics for intelligence and photonics control

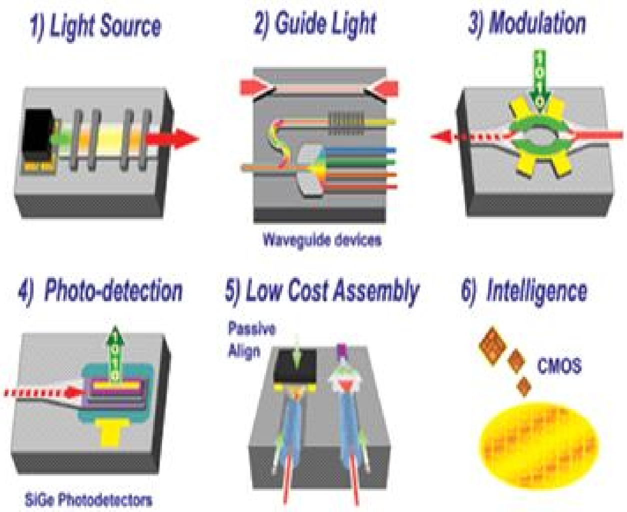

Figure 1.building blocks in silicon photonics

The key challenges that were met in the development of silicon photonics are:

- Light source.
- Silicon waveguide.
- Silicon modulators.
- Photo detector.

A. Light source

Silicon is an inefficient light emitter because of a fundamental limitation called an indirect band-gap. An indirect band-gap prevents the atoms in silicon from emitting photons in large numbers when an electrical charge is applied. Instead, silicon emits heat. Silicon is capable of routing, modulating, and detecting light; silicon has needed an external light source to provide the initial light. These external light sources are generally discrete lasers and require careful alignment to the silicon waveguides [3], [7]. The problem is that accurate alignment is difficult and expensive to achieve. Even submicron misalignment of the laser to the silicon waveguide can render the resulting photonic device useless. A long-standing quest in silicon photonics has been the creation of a laser source that can be manufactured directly on the silicon photonic chip, in high volume, and whose emitted light is automatically aligned with the silicon waveguide.

B. Hybrid Silicon Wave Guide

The silicon substrate was the base upon which the other items were placed. On this substrate rests the silicon waveguide [14]. Both the substrate and the waveguide were manufactured using standard silicon fabrication processes. When the silicon and the indium phosphide based material were heated and pressed together, the two oxide layers fused them together [7]. When the voltage was applied, the light generated in the indium phosphide based material passed directly through the glue layer into the silicon waveguide below, which acted like the laser cavity to create the hybrid silicon laser. The design of the individual silicon waveguides was critical in determining the performance of the hybrid silicon laser, and would allow future versions to be built that generate specific wavelengths.

C. Silicon Modulators

One key problem was making high speed modulators, since silicon was not electro-optic due to its inversion symmetry [10]. This leaves carrier-optic and thermo-optic effects as the primary mechanisms for modulation in silicon and due to the relatively long carrier lifetime in silicon are slow under carrier injection. The first demonstration of a Gigabit modulator was in 2004, utilizing an MOS based structure under depletion. Progress in this area has been very rapid by many groups around the world. A recent, exciting advance is the 40 Gbit/s silicon modulator [12] demonstrated by Intel.

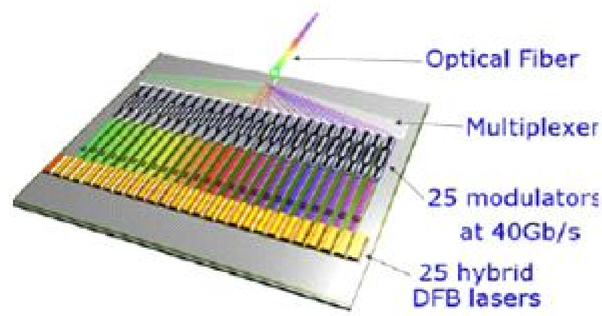

Figure 2. A 1 Tbit/s transmitter made out of silicon technology

D. Photo detector

The use of Ge was important because, unlike Si, it could efficiently detect light in the near infrared which was the standard for communications. The drawback was that so much stress was developed in pure Ge films deposited on Si that defects were introduced near the Ge/Si interface. Careful design and processing were needed to minimize the impact of these defects on the electrical performance of the device. This was now a different type of Ge/Si photo detector that has built-in amplification, which makes it much more useful in instances where very little light falls on the detector. It is called an avalanche photo detector. Because an avalanche process occurred inside the device. In order to realize the full performance potential from this materials, it was needed to further reduce the dark current that was coming from the defects at the Ge/Si interface, and stop the inter diffusion of Ge and Si that occurred during annealing [7]. This intermixing was problematic since the Ge caused higher noise than if the silicon alone was in the multiplication region. If we are successful, this work will pave the way for developing low cost, CMOS-based Ge/Si APD operating at data rates of 40Gbps or higher in the future.

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VII. Applications

Silicon photonics has its wide range of applications in

- Optical communication.
- Data com and telecom applications.
- VOA's.
- ROADM's.
- Silicon Triplexer.
- Ring resonators.
- Optical shifter /mirror.
- Optical multi channel separating filter.
- Modulated Raman laser.
- Raman amplifier.
- Wavelength converters.
- Splitters and couplers.
- Attenuators and deflectors.

VIII. Challenges

A. Compatibility-quad

"Compatibility-quad" describes conditions that must be met by silicon photonics to be fully compatible with VLSI electronics.

Material Compatibility ✓	**Process Compatibility** ✓
Economic Compatibility ?	**Heat Compatibility** ?

Figure 3. Compatibility–quad describing conditions that must be met by silicon photonics to be fully compatible with VLSI electronics

B. Material compatibility and process compatibility

The vision of silicon photonics has been the introduction of photonics into silicon CMOS manufacturing process, thus silicon is process compatible. Silicon can guide light through it because it is transparent at the infrared Wavelengths at which optical communication systems operate so; photonics is material compatible [1].

C. Economic compatibility

The external light sources were generally lasers and they required careful alignment to the silicon wave guide. The problem here was that accurate alignment was difficult and expensive to achieve. Even submicron misalignment of the laser to the silicon waveguide could render the resulting photonic device useless [1]. This required expensive processing methods for accurate alignment of lasers to the silicon waveguides.

D. Heat compatibility

Heat compatibility requires that photonic devices must be able to operate on the hot VLSI substrate and that their own power dissipation should be negligible. For photonics to merge with VLSI electronics, it cannot significantly increase the chip area. Increase in power density of VLSI chips, where today's level of 100 W/cm2 challenges even the most advanced packaging technologies. The problem of heat dissipation was so severe that it threatens to bring to halt the continued advance of the technology, as described by Moore's law. This fact was highlighted by the recent shift of the microprocessor industry away from increasing the clock speed and in favor of multi-core processors. Among photonic components, lasers were the most power hungry photonic devices [1],[3].

The lack of an electrically pumped Si Laser, to date, dictates an architecture where the light source remains off-chip. Far from being a compromised solution, this architecture was in fact preferred as it removed a main source of heat dissipation. Furthermore, the performance degradation of injection lasers at high temperatures will be a major obstacle to their integration onto the hot VLSI substrate [1].

IX. Proposed solution to overcome the challenges

Instead of using silicon wafer if we build it with the gallium nitride of two inch in size which is almost 1/6th the diameter of standard silicon wafer can be used in producing violet laser [4]. At the same time we can have double digit rate of growth, if the size of gallium nitride is made 100mm or more. It can be used to conduct heat far better than silicon. By making substrates from gallium nitride we can provide better foundation for diodes and transistors [4]. Gallium nitride families can produce LED'S with outputs ranging from the ultraviolet to infrared. Using gallium nitride as wafer is one of the key challenges i.e., heat dissipation can be eliminated since it won't succumb below a temperature of 2225 æ%c and pressure of 64000 atmospheres. This GaN structure is created through a combined approach of a layer-by-layer template fabrication technique and selective metal organic chemical vapor deposition (MOCVD). These GaN 3DPC exhibit a stacking direction band gap characterized by strong optical reflectance between 380 and 500 nm. By introducing a "line-defect" cavity in the fifth (middle) layer of the 3DPC, a localized transmission mode with a quality factor of 25–30 is also observed within the photonic band gap

X. Conclusion

This paper has been an attempted overview of the silicon photonics and its application areas, the current state of device technology, and the challenges that lie ahead on the path to commercial success. Silicon photonics is on the verge of becoming a viable technology for various applications especially in communication and internet. Already, commercial components such as optical transceivers are available based on the technology. "Economic" and "heat" compatibility with silicon microelectronics are the main challenges ahead.

DOI: 01.IJCOM.02.03. 524

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DOI: 01.IJCOM.02.03.524